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Technology Change and the Economics of Silvicultural Investment

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Financial anaylses of intensive and low-cost reforestation options are conducted for two predominant timber types in the United States: loblolly pine (*Pinus taeda* L.) stands with hardwood competition in the South, and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and red alder (*Alnus rubra* Bong.) stands in the Pacific Northwest. Results show that the expected present values (EPVs) of low-cost options that result in mixtures of conifers and hardwoods are superior, in some situations, to the EPVs of the intensive options. For the loblolly pine type, the low-cost option is superior when markets exist for both pine and hardwood thinnings. For the Douglas-fir type, the low-cost option is superior when precommercial thinning of red alder is an option. In both cases, it is assumed that conifers are likely to dominiate hardwoods after reforestation. The low-cost options are superior in these situations, because mixed-species stands include the option to change species composition and density in mid-rotation, contingent on the relative stumpage prices. Results suggest that low-cost regeneration options may satisfy both economic and environmental objectives that are difficult to attain with intensive forest practices.

Keywords: Decision analysis, even-aged management, low-cost management, *Pseudotsuga menziesii*, *Alnus rubra*, *Pinus taeda*.

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Technology Change and the Economics of Silvicultural Investment

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INTRODUCTION

The 1989 RPA Assessment of the timber situation in the United States documents substantial opportunities to increase timber production on private forests (Haynes 1990). Because of the expected benefits to society from increased timber supply, the Assessment identifies economically attractive reforestation and stand improvement treatments that can increase timber production. The Assessment focuses on high-intensity management, but ignores both market risk and the economic potential of low-cost reforestation practices. This report investigates the effects of market risk on the economics of both intensive and low-cost reforestation practices.

Reforestation investments are risky because of the long time between reforestation and harvest. In the southern United States, for example, rotations for loblolly pine (*Pinus taeda* L.) plantations are between 20 and 40 years, and in the Pacific Northwest, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is grown for 50 years or more. While trees mature, changes in timber markets may substantially impact stumpage prices and the economics of reforestation investments. Technological changes in the harvesting and processing of logs may affect timber demand. For example, increased use of both recycled paper and hardwood chips in pulp production may reduce the demand for softwood pulpwood, especially in the South (Ince 1990). On the supply side, regulations requiring environmental protection on public and private lands may substantially reduce the amount of timber available for harvest. For example, Adams and Haynes (1990) estimate that the conservation strategy for the northern spotted owl will reduce the annual timber harvest on national forests, in the Pacific Northwest, by about 40%, compared to the average annual harvest over the past two decades. How these and other market forces affect future stumpage prices is not known. This market risk needs to be considered in economic analyses of reforestation investments.

Intensive timber management is not appropriate everywhere. Many non-industrial forest landowners may prefer less intensive management, because they lack capital, they are unwilling to bear the risks of long-term investments, or they desire amenities that result from structurally diverse, mixed-species stands (USDA Forest Service 1990). The economic returns from timber management regimes that require low capital investment and maintain species diversity need to be examined. The results will provide landowners with economic information about a wider range of management options.

OBJECTIVES

This report describes financial analyses of the effects of market risk on both intensive and low-cost reforestation practices for two case studies: loblolly pine stands with hardwood competition in the Southeast and Douglas-fir and red alder (*Alnus rubra* Bong.) stands in the Pacific Northwest. In both cases the objectives are:

- to estimate the effects of market risk on the economic returns of both intensive and low-cost reforestation practices, and
- to identify reforestation strategies that maintain options to adapt to future market changes.

Each case is presented in three sections. The first is a review of previous studies, which include the economics of intensive and low-cost reforestation options, and the changes in technology and environmental regulations that may impact future stumpage prices.

The second section outlines the structure of the investment analysis. The investment analysis is formulated with a decision tree that includes up to four kinds of management options: regeneration, precommercial thinning, commercial thinning, and rotation age. The regen-

eration options span a range from low-cost to intensive treatments. For each species, the stumpage price trend, which is the average annual real rate of price change over the first 15 years of management, is a random variable. Each random variable is modeled with a triangular probability distribution that is formulated by taking into account the potential market impacts of changes in technology and environmental regulation. Short-term (e.g., quarterly) stochastic changes in stumpage price are ignored to focus attention on the effects of long-term price trends. A separate procedure is used to analyze the effects of short-term market risk on optimal harvest policies for loblolly pine.

The third section presents the results. The decision tree is used to determine treatments that maximize the expected present value (EPV) of the stand as a function of the stumpage prices. The results include estimates of the EPVs of reforestation options and rules for adjusting mid-rotation treatments as new price information becomes available. Stochastic simulation is used to estimate a range of present values for the regeneration options.

LOBLOLLY PINE MANAGEMENT

Previous Work

In most of the southern United States, loblolly pine trees may be sold for sawtimber or pulpwood, and expectations about prices for these products affect the economics of plantation management options (Arthaud and Klemperer 1988; Broderick et al. 1982; Hardie 1977; Hotvedt and Straka 1987; Roise et al. 1988). With a price premium for sawtimber, optimal management involves low planting densities (400 to 450 trees/ac), one or two commercial thinnings, and 30- to 40-year rotations. When stumpage price is independent of tree size (e.g., for pulpwood production), economic returns are maximized using a high planting density, a short rotation, and no thinning. For pine plantations with hardwood competition and hardwood removal costs of about $50/ac, hardwood treatment during the first 10 years to create a pure pine plantation increases present value substantially (Alig et al. 1981; Klemperer et al. 1987; Valsta and Brodie 1987). However, the present value of a low-cost site preparation and planting treatment that results in a low level of hardwood competition can be as high as that of intensive plantation management (Hepp 1989).

For comparison with plantations, there are few studies of natural stand yields. Nevertheless, it is commonly believed that, even with hardwood control, naturally regenerated pine stands produce less wood volume that is distributed among more trees with smaller diameters. Results from Campbell's (1985) comparison of direct seeded and planted pine plots provide supporting evidence. At age 20, trees in the seeded plots are more numerous, less uniformly spaced, and smaller than trees in the planted plots. Merchantable volumes in seeded plots are 6% to 28% less than volumes in planted plots. Guldin and Baker (1988) compare yields after 36 growing seasons, in natural and planted stands of loblolly and shortleaf (*Pinus echinata* Mill.) pine. Total merchantable yield in natural stands is as little as 50% of plantation yield.

Compared to an intensive reforestation effort, the economic advantage of natural regeneration is the smaller cost of stand establishment. However, the disadvantage is lower volume yield. When the cost difference between planting and natural regeneration is the planting cost (e.g., $75/ac), the present value of natural regeneration is about 20% less than the present value of intensive site preparation and planting (Dangerfield and Edwards 1990; Guldin and Guldin 1990). When the cost difference between the two treatments is higher (e.g., $170/ac, representing planting and hardwood control costs), the present value of natural regeneration is greater (Franklin 1989).

These studies assume that stumpage prices are fixed and known with certainty. However, future prices are uncertain, and this uncertainty may affect the economics of reforestation investment. At least three forces may impact softwood and hardwood stumpage prices in the South. First, implementation of the conservation strategy for the northern spotted owl and other environmental protection measures will restrict national forest timber harvests, particularly in the western United States (Adams and Haynes 1990). This reduction generates potential increases in the demand for timber products and stumpage in the South, as consumers look for cheaper products (Adams and Haynes 1991). Second, in a major public commitment to recycling, the U.S. paper industry announced a goal of 40% wastepaper recovery in paper production by 1995 (Ince 1990). Attaining this goal would reduce the demand for pulpwood, particularly in the South. Finally, in response to relatively low hardwood stumpage prices, the paper industry is projected to adopt technology for hardwood processing that would increase the demand for hardwood pulpwood nation-wide (Ince 1989).

Using economic models from the 1989 RPA Assessment, Adams and Haynes (1991) and Ince (1990) project the impacts of these forces on timber markets in the South. For the 1990s-2010s, forecasts of the average annual real rates of change in the price of southern pine sawtimber range from 0.0% to 4.0%. The 4.0% projection results from restricted national forest timber harvests nation-wide, combined with a shortage of private timber of merchantable age in the South. If recycling increases dramatically, reductions in demand offset these supply limitations, so that the pine sawtimber price is constant in real terms. Between 2020 and 2040, the real price of pine sawtimber is projected to stabilize or fall because of increases in timber supply resulting from reforestation efforts in the 1980s and 1990s. Delivered softwood pulpwood prices are projected to increase at an annual rate of 0.6% to the year 2040; however, with increased recycling, the projected price is constant. Regardless of the level of recycling, the delivered hardwood pulpwood price, which has historically been less than the softwood price, is projected to equal the softwood price by the year 2010. Higher delivered hardwood prices should lead to higher hardwood stumpage prices.

An additional source of uncertainty is the short-term change in stumpage price. For example, while the trends in sawtimber and pulpwood stumpage prices in the Piedmont region of North Carolina have been flat over the past decade, monthly prices have varied by up to 40% of their means (Haight and Holmes, 1991). The underlying stochastic price process can be estimated with a regression model using the past price observations. This model, in turn, can be used to predict price changes and construct harvest policies.

Depending on the form of the price model, harvest policies that anticipate price changes can be constructed to improve economic returns. With stationary price models, optimal harvesting follows a reservation price policy in which cutting takes place when price is above the historical average (Brazee and Mendelsohn 1988; Haight and Smith 1991; Lohmander 1988; Norstrom 1975). As the variance in the price process increases, the EPV of a reservation price policy increases in comparison to that of a fixed rotation age. With a non-stationary random walk model, optimal harvesting depends on fixed costs; with none, the policy is a fixed rotation age with no gain in EPV. Otherwise, the policy is price-dependent (Thomson, 1992).

Methods

Economic Analysis with Stochastic Price Trends

The study investigates the effects of stochastic stumpage price trends for pulpwood and sawtimber on the economics of reforestation options, for loblolly pine stands with hardwood competition. The results are obtained with a decision tree, described in detail by Haight (1993). Management takes place on site index 65 (25-year basis) land, in the coastal plain region, of the southeastern United States. The sensitivity analysis includes results for site indices 55 and 75.

Three regeneration options are defined to span a range of treatment intensities. The high technology option (HITEC) involves intensive site preparation (shearing, raking, piling, and burning), planting 700 pine seedlings/ac, and chemically removing hardwoods. The cheap option (CHEAP) involves planting 700 pine seedlings/ac, and allowing natural hardwood regeneration to grow (e.g., Phillips and Abercrombie 1987). Costs are reduced by less intensive site preparation (chopping and burning) and no chemical release. The third option (NATURAL) involves light site preparation (shearing) and natural regeneration, which is assumed to provide 1,200 trees/ac (pine) in the first year.

The planting densities for the HITEC and CHEAP options are higher than those recommended for sawtimber production in the studies cited. However, assuming that markets exist for commercial thinning, management regimes that combine high planting densities and commercial thinning options are economically superior to regimes that specialize in either sawtimber or pulpwood production without thinning options (Haight, 1993). A high planting density preserves the option to produce high levels of either sawtimber or pulpwood, depending on their mid-rotation stumpage prices. Further, when the sawtimber price is relatively high, pulpwood thinning provides early economic returns without sacrificing sawtimber production later in the rotation.

The pine and hardwood densities in year 15 depend on the site index and the regeneration option (table 1). As the intensity of the regeneration effort decreases, the basal area of hardwoods increases.

Because the HITEC option includes chemical release, no hardwoods are present throughout the rotation. In both the CHEAP and NATURAL, options, about 30% of the stand basal area is made up of hardwoods.

Table 1.—Loblolly pine (LP) and hardwood (HW) densities per acre 15 years after regeneration.

Site index	HITEC LP (trees)	HITEC LP (ft^2)	HITEC HW (ft^2)	CHEAP LP (trees)	CHEAP LP (ft^2)	CHEAP HW (ft^2)	NATURAL LP (trees)	NATURAL LP (ft^2)	NATURAL HW (ft^2)
55	590	93	0	574	77	33	928	94	40
65	574	120	0	542	96	41	828	111	48
75	551	144	0	511	113	48	746	125	54

The management options after regeneration include commercial thinning, final product, and rotation age. Commercial thinning may take place when the quadratic mean diameter of the stand is greater than 5.5 in. For site indices 65 and 75, commercial thinning is in year 15 (HITEC and CHEAP) or year 20 (NATURAL). For site index 55, commercial thinning is in year 20 or 25. Pine trees may be thinned to a minimum of 100 trees/ac and merchandized as pulpwood (ft^3/ac). If present, hardwoods are either removed and merchandized as pulpwood (ft^3/ac) or are left standing. In the final harvest, pine may be merchandized as pulpwood or a mixture of sawtimber and pulpwood. Sawtimber volume is expressed in International thousand board feet (mbf). If present, hardwoods are merchandized as pulpwood.

Table 2.—Loblolly pine sawtimber and pulpwood yields[1] by age, for management regimes that emphasize either sawtimber or pulpwood production, on site index 65 land.

Age	HITEC (mbf/ac)	HITEC (mcf/ac)	CHEAP (mbf/ac)	CHEAP (mcf/ac)	NATURAL (mbf/ac)	NATURAL (mcf/ac)
A. Sawtimber production[2]						
20	1.7	0.7	1.3	0.7	0.0	1.6
25	6.1	0.6	5.5	0.6	0.1	2.5
30	10.8	0.5	10.1	0.5	1.1	3.0
35	15.3	0.5	14.3	0.5	3.8	3.1
B. Pulpwood production[3]						
20	0.0	2.4	0.0	1.8	0.0	1.6
25	0.0	3.3	0.0	2.7	0.0	2.5
30	0.0	4.0	0.0	3.2	0.0	3.3
35	0.0	4.7	0.0	3.9	0.0	4.0

[1]*Sawtimber yield is International thousand board foot (mbf) per acre; pulpwood yield is thousand cubic feet (mcf) per acre.*

[2]*For the HITEC and CHEAP regeneration options, the yield table assumes that commercial thinning in year 15 reduces softwood density to 100 trees/ac and removes all hardwoods. For the NATURAL option, the yield table assumes no commercial thinning.*

[3]*The yield table for each regeneration option assumes that only hardwoods are removed in the commercial thinning.*

The growth and yield of pine and hardwoods are forecast with the North Carolina State University Plantation Management Simulator (Hafley and Buford 1985; Smith and Hafley 1986, 1987). The simulator is used to project measures of stand density after commercial thinning, and continuing forward to rotation age. The simulator estimates softwood and hardwood yields as a function of stand density. Loblolly pine yields for representative management regimes, for each regeneration option, are listed in table 2. Note that the NATURAL and CHEAP options that emphasize pulpwood production produce 15% to 25% less volume than the HITEC option (table 2B).

There are several economic assumptions included in the decision analysis. All prices and costs are in 1988 dollars. The regeneration costs are directly related to the intensity of regeneration treatment, and represent averages for the coastal plain region (Straka et al. 1989). The HITEC option costs $225/ac; the CHEAP option costs $115/ac; and the NATURAL option costs $50/ac.

Softwood sawtimber and pulpwood stumpage prices for thinnings and final harvests are expressed as probability histograms (fig. 1). The price distributions take effect in year 15, and are constant over the rotation.

The sawtimber price distribution (fig. 1A) is an optimistic appraisal of future prices. Prices range from $120 to $280/mbf; the most likely price class is $240/mbf. For

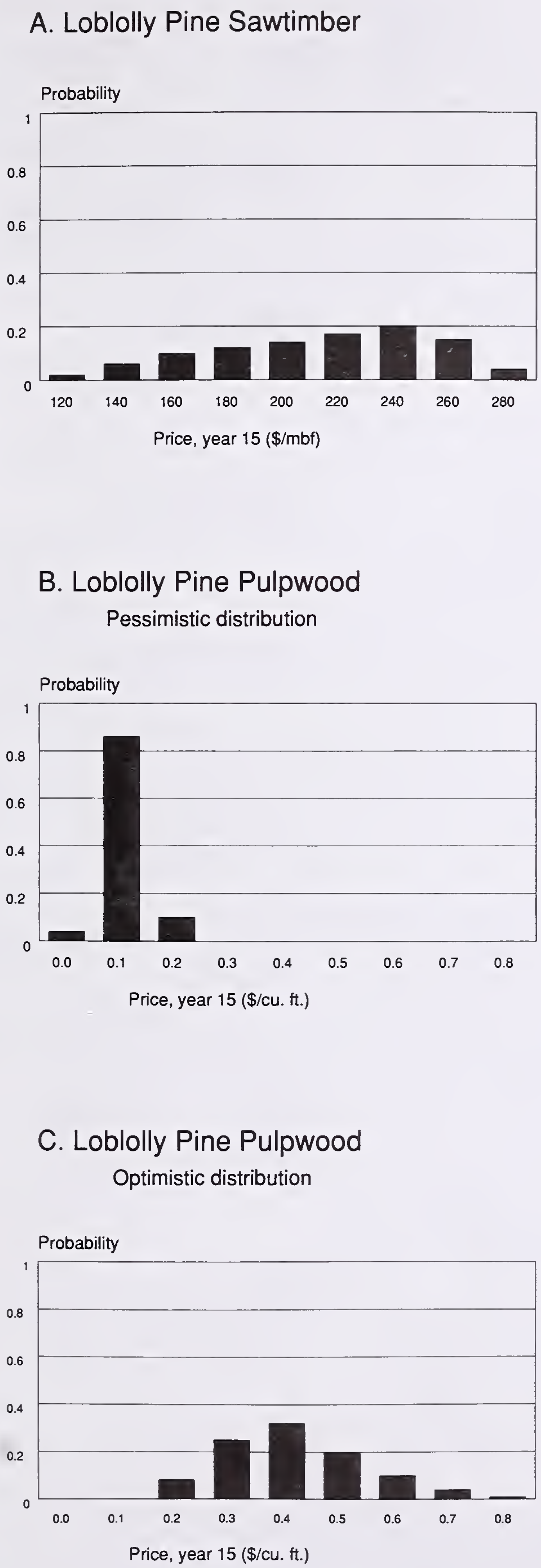

Figure 1.—Probability histograms for loblolly pine stumpage prices in year 15.

comparison, the 1992 South-wide average sawtimber price is $140/mbf (1988 dollars), as reported by Timber Mart-South. The average price during the 1980s is $125/mbf, with no significant trend. The most likely price forecast ($240/mbf) represents a significant increase (4% average annual rate) over the next 15 years.

The pulpwood price distributions represent two different outlooks. In the pessimistic distribution (fig. 1B), prices range between $0.00 and $0.20/ft^3, with a most likely class of $0.10/ft^3. In the optimistic distribution (fig. 1C), prices range between $0.20 and $0.80/ft^3, with a most likely class of $0.40/ft^3. For comparison, the 1992 South-wide average pulpwood price is $0.24/ft^3.

In the baseline runs, the hardwood pulpwood price is assumed to be the same as the softwood pulpwood price in year 15. For comparison, the 1992 South-wide average hardwood pulpwood price is 40% of the softwood pulpwood price. To examine the effects of less optimistic forecasts, sensitivity analysis is conducted assuming that hardwood pulpwood prices are less than 50% of softwood pulpwood prices.

Each price distribution is computed using Monte Carlo simulation, based on assumptions about the initial stumpage price and the price trends. The initial sawtimber price is $140/mbf, which is the 1992 South-wide average. Representing a range from low to high values, the initial red alder pulpwood price is either $0.10 (fig. 1B) or $0.40/ft^3 (fig. 1C). The trends for sawtimber and pulpwood prices during the first 15 years are independent random variables with triangular probability distributions. A triangular distribution is used when little is known about the underlying distribution of the random variable (Law and Kelton 1982, p. 204). The parameters of a triangular distribution include minimum and maximum values and the most likely value. For the sawtimber price distribution, the minimum and maximum trends are –1% and 5%, respectively, with a most likely trend of 4%. For the pulpwood price distributions, the minimum and maximum trends are —5% and 5%, with a most likely trend of 0%.

At rotation age, the returns include the revenue from clearcutting and the value of bare land. The bare land value is the present value of an infinite series of rotations, assuming no risks in future management. The real discount rate is 4%. Taxes and management costs are not included.

The purpose of the decision analysis is to determine optimal values for the management options as a function of sawtimber and pulpwood stumpage prices, and to determine the EPVs of the regeneration

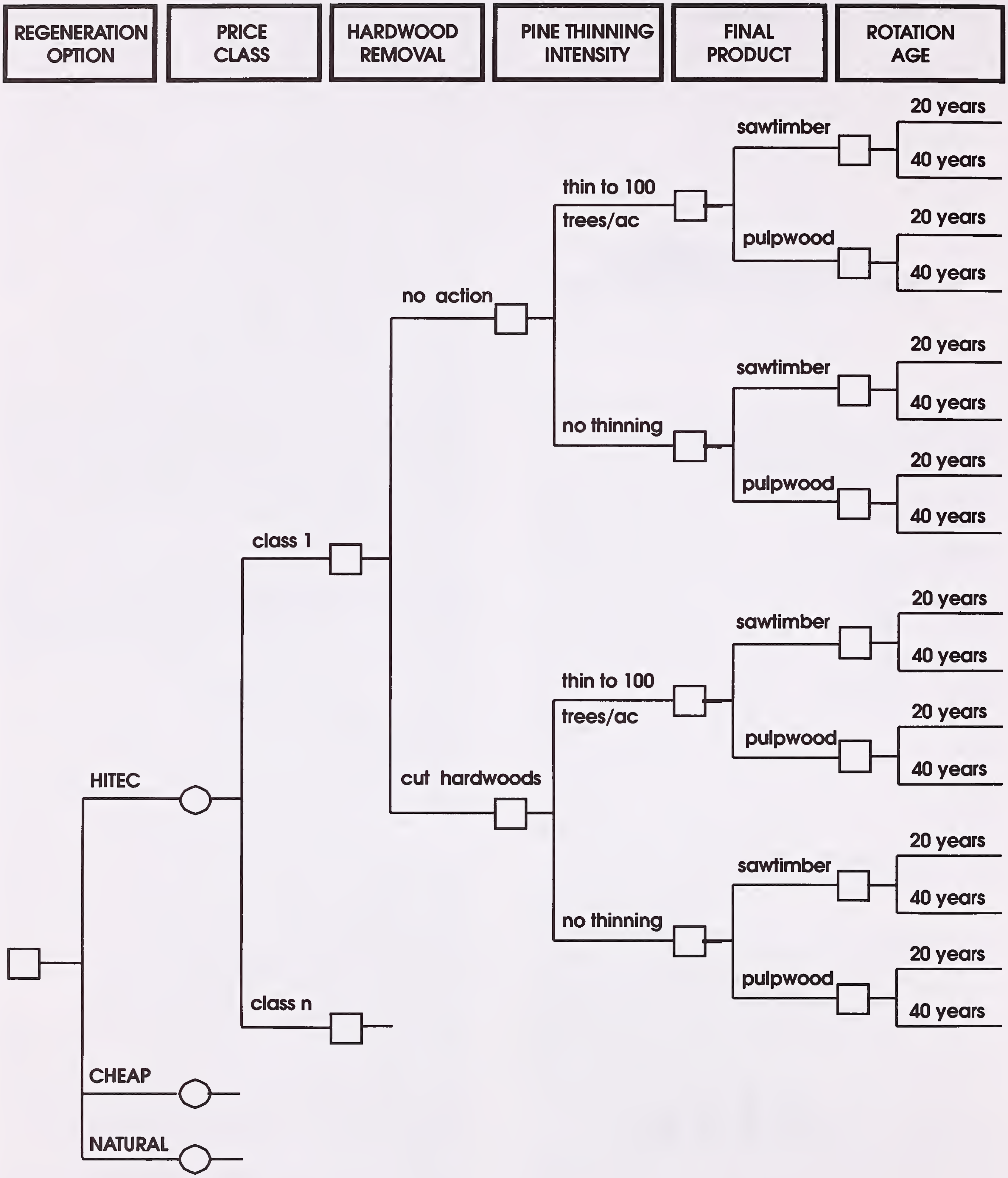

Figure 2.—A portion of the decision tree for determining optimal management actions for loblolly pine stands with hardwood competition.

options. The analysis is described using the decision tree in figure 2. The management decisions are represented by square boxes, and proceed from left to right over time, from regeneration and thinning to final product and rotation age.

For each regeneration option, the analysis starts with the rotation age decision and moves backward in time (from right to left in the decision tree). The optimal rotation age is determined for each combination of final product, post-thinning stand density, and stumpage price class. Next, the final-product decision is made by comparing the present values of the optimal rotation ages for the product classes. Then, the commercial thinning decision is made by comparing the present values of different thinning intensities, including no thinning and hardwood removal. Present value is the sum of the discounted value of the pulpwood thinning yield and the present value of the corresponding optimal final product and rotation age decisions.

The EPV of each regeneration option is a random variable, because the stumpage prices in year 15 are stochastic (represented by a circle in the decision tree). The EPV is computed as the difference between the weighted average of the present values of the optimal thinning decisions across the price classes and the planting cost.

Economic Analysis with Stochastic Quarterly Prices

So far, the methodology has focused on determining the effects of stochastic stumpage price trends on the economics of reforestation options. Different methods are needed to estimate the effect of short-term stochastic price changes on the clearcutting decision. Methods and results for this analysis are presented in detail in Haight and Holmes (1991).

The structure of the stochastic process that produces short-term price changes is determined by analyzing a quarterly series of loblolly pine sawtimber stumpage prices. The price observations are from the Piedmont region of North Carolina. The series is tested for stationarity using the so-called augmented Dickey-Fuller test (Dickey et al. 1986; Said and Dickey 1984) before model estimation.

A discrete-time, dynamic programming algorithm is used to determine how the stochastic price model affects the optimal harvest policy and EPV of a 30-year-old, fully stocked, loblolly pine plantation. The decision model is for a single rotation; the problem is to choose the optimal clearcut strategy for the mid-rotation stand that maximizes its EPV. Revenue includes the value of the harvested trees and the value of bare land, which is independent of price and time and known with certainty.

Results

Regeneration and Commercial Thinning

For each site index and pulpwood price distribution, the CHEAP regeneration option has the highest EPV (table 3). The EPVs of the CHEAP option are up to 16% greater than EPVs of the HITEC option. The CHEAP option is superior to the HITEC option, primarily because it does not incur the cost of precommercial hardwood removal. Instead, all of the hardwood trees, together with a portion of the pine trees, are removed in a commercial thinning, with only a small reduction in softwood sawtimber and pulpwood yield at rotation age (table 2A). The EPVs of the CHEAP option are up to 25% greater than EPVs of the NATURAL option. The CHEAP option is superior, because the density-dependent competition in the naturally regenerated stand impedes tree diameter growth and sawtimber production.

Table 3.—Mean[1] and minimum present values for loblolly pine regeneration options with commercial thinning.

Pulpwood price distribution	Regeneration options					
	HITEC		CHEAP		NATURAL	
	mean	min	mean	min	mean	min
	($/ac)					
	Site index 55					
pessimistic	347±5	171	393±4	228	337±3	221
optimistic	482±6	234	490±5	269	462±5	280
	Site index 65					
pessimistic	788±9	425	850±9	501	659±6	409
optimistic	966±10	521	1,007±10	589	773±7	469
	Site index 75					
pessimistic	1,081±13	575	1,189±13	702	896±9	550
optimistic	1,189±13	649	1,408±14	825	1,094±10	642

[1]*Mean present values include an approximate 95% confidence interval.*

Table 4.—Thinning and final harvest decisions for loblolly pine regeneration options as a function of the mid-rotation pulpwood price. The mid-rotation sawtimber price is $140/mbf, and the site index is 65.

Pulpwood price ($/ft³)	Regeneration options											
	HITEC				CHEAP				NATURAL			
	Thinning[1]		Final harvest[2]		Thinning		Final harvest		Thinning		Final harvest	
	HW	LP	Prod	Age	HW	LP	Prod	Age	HW	LP	Prod	Age
0.5	No	Yes	S	35	Yes	Yes	S	35	Yes	No	S	33
0.6	No	Yes	S	35	Yes	Yes	S	35	Yes	No	S	31
0.7	No	Yes	S	35	Yes	No	P	25	Yes	No	P	31
0.8	No	No	P	25	Yes	No	P	25	Yes	No	P	31

[1]*Commercial thinning options include complete hardwood (HW) removal and loblolly pine (LP) thinning. With HITEC reforestation, hardwoods are removed within 5 years of pine establishment; so, there is no hardwood commercial thinning.*

[2]*Final harvest options include the softwood product (Prod), which may be sawtimber (S) or pulpwood (P), and rotation age.*

Softwood commercial thinning intensity and subsequent final product and rotation age depend on the mid-rotation stumpage prices. When the sawtimber price in year 15 is high (>$160/mbf), commercial thinning and sawtimber production is superior for all regeneration options, regardless of the pulpwood price. When the sawtimber price is low, the prescription is more complex. Table 4 shows the best actions for a site index 65 stand, when the sawtimber price in year 15 is $140/mbf. For the HITEC and CHEAP options, commercial thinning is superior to no thinning for all but the highest pulpwood prices. Commercial thinning is recommended, because it provides early economic returns while increasing sawtimber production with relatively long rotations (35 years). When the pulpwood price is high, pulpwood production is emphasized with no commercial thinnings and shorter rotation ages (25 years). For the NATURAL option, commercial thinning is not recommended, because density-dependent competition has reduced the potential for sawtimber yields. Higher economic return is obtained by producing a mixture of softwood sawtimber and pulpwood.

A feature of the CHEAP and NATURAL options is the presence of hardwoods after regeneration. Hardwoods should be completely removed in a commercial thinning regardless of the pulpwood price at the time of thinning. In addition to providing pulpwood revenue, hardwood removal increases the total return from softwood sawtimber and pulpwood at rotation age.

These results show that the CHEAP regeneration option has the highest EPV when markets exist for softwood and hardwood thinnings, andwhen the hardwood pulpwood price is the same as the softwood pulpwood price. How do less optimistic hardwood price assumptions affect the EPV of the CHEAP option? Whenever hardwoods have commercial value, the CHEAP option retains its EPV ranking. For example, when the hardwood price is projected to be 50% of the softwood pulpwood price, the EPVs of the CHEAP option do not significantly change. However, when hardwoods have no commercial value and cost money to remove, the HITEC option has the highest EPV. For example, if hardwoods cost $100/ac to remove in year 15, the EPVs of the CHEAP option are about 15% less. In this case, the EPVs of the HITEC option are up to 11% greater than the EPVs of the CHEAP option.

Do the rankings change if markets do not exist for any commercial thinning? When commercial thinning is not an option, the EPV of the HITEC treatment is the highest. For the site index 65 stand, the EPVs of the HITEC option are up to 15% greater than the EPVs of the CHEAP option. The CHEAP option loses value, because hardwoods are present thoughout the rotation, and the mixed-species stand is less productive than a pure pine stand.

Final Harvest

So far, the results have focused on the effects of 15-year price trends on the EPVs of alternative regeneration strategies. What is the effect of short-term price changes on the economics of harvest strategies for mid-rotation stands? The results begin with the determination of a quarterly price model and move to the determination and evaluation of various harvest policies.

For the quarterly price series, the statistical evidence supports a first-order, autoregressive model. Evidence of autocorrelation in the price series has implications for long-term forecasts, market efficiency, and optimal harvest policies. Forecasts with an autoregressive model approach the mean of the historical series, regardless of the level of the most recent price observation. Because the current price is used to predict future prices, the autoregressive model is not consistent with the necessary condition for an efficient market. As a result, the predictive power of past prices may be used to construct adaptive harvest policies that time timber harvests to periods of high prices, and, consequently, increase the likelihood of higher returns.

With the autoregressive price model, the optimal cutting policy for a 30-year-old loblolly pine stand is to harvest when the observed price is greater than an age-dependent reservation price. Reservation prices decrease with age and approach the mean of the price series ($125/mbf) (fig. 3). The area below the curve contains the price-age combinations when harvesting should be postponed. The EPV of the 30-year-old stand is $2,183/ac. The expected rotation age is 36 years.

The rationale for the price-dependent cutting policy is as follows. Stationary autoregressive models produce price paths that fluctuate around the mean of the historical series. It is better to postpone cutting when the price is below average, because there is a high probability that a future price will be above average. Conversely, it is better to cut when price is above average, because price is likely to drop in the future.

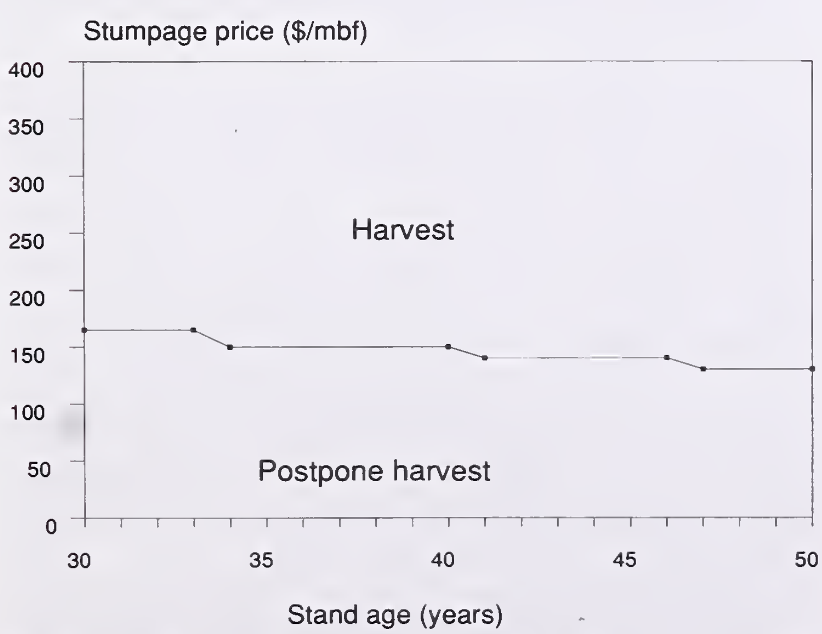

Figure 3.—Optimal reservation prices for harvesting a mid-rotation loblolly pine stand.

For comparison with the performance of the optimal reservation price policy, Monte Carlo simulation is used to estimate the EPVs of fixed rotation ages, when the price process is governed by the autoregressive model. The costs of fixed rotation ages are large; the EPV of the optimal rotation age ($1,786/ac, 34 years) is 18% less than the EPV of the optimal reservation price policy ($2,183/ac). The cost results from not using the predictive power of the current price to time the harvest.

Using the reservation price policy on a quarterly interval requires the monitoring of stumpage prices and a readiness to complete a sale contract. The cost of these activities may affect the value of the policy. With a fixed cost assessed each quarter before harvest, the optimal reservation prices and the expected rotation age decrease. Harvesting is acceptable at lower prices to avoid paying for additional price monitoring. The EPVs decrease and approach $1,752/ac, the value of the 30-year-old stand cut immediately. With a cost of $15/ac, the expected rotation age is 32.5 years.

A possible advantage of a fixed rotation age is that costs of price monitoring are avoided. How does the EPV of the optimal rotation age compare? With quarterly costs less than about $20/ac, the optimal reservation price policy for the quarterly interval provides higher EPVs.

DOUGLAS-FIR AND RED ALDER MANAGEMENT

Previous Work

Financial analyses of pure Douglas-fir plantations examine the effects of sawtimber price assumptions on the economics of alternative management strategies (Brodie and Kao 1979; Brodie et al. 1978; Marshall 1991; Riitters et al. 1982). Under a price premium for large diameter trees, present value is maximized with a low planting density (<300 trees/ac), heavy commercial thinnings, and a long rotation age (>70 years). When price is independent of tree diameter, the planting density is higher, thinnings are lighter, and the rotation is shorter.

The effects of vegetation control also have been studied. In the coast range of Oregon and Washington, red alder is a prime competitor with Douglas-fir; and it is commonly accepted that economic returns are enhanced by limiting red alder competition. For example, Brodie et al. (1987) find that untreated stands dominated by red alder have substantially lower present values than do

treated stands that are dominated by larger and more vigorous Douglas-fir. They conclude that large investments in red alder control during Douglas-fir reforestation are economical, when the alternative is a stand completely dominated by red alder and when red alder has little economic value relative to Douglas-fir.

In comparison to these conclusions, the economics of Douglas-fir plantations change when the degree of red alder competition is stochastic. Cleaves and Birch (1991) estimate the EPVs of reforestation strategies that have a range of site preparation, vegetation control, and total cost. The higher the cost is, the greater is the probability of Douglas-fir dominance. Results show that the differences between EPVs of reforestation strategies are small (<10% of the highest value), even though cost differences are high. The cheapest reforestation treatment, which does not include red alder control, provides near-optimal returns, on average, because the likelihood of successful Douglas-fir establishment is high, and because replanting takes place upon failure.

The economics of Douglas-fir and red alder management may change when uncertainty in timber markets is taken into account. There is substantial uncertainty in the long-term trend in the stumpage price for Douglas-fir sawtimber. Adams and Haynes (1990) and Ince (1990) estimate the price impacts of possible timber supply limitations and recycling scenarios between the years 1990 and 2040. Assuming that the national forest harvest level in the Pacific Northwest falls dramatically because of the conservation strategy for the northern spotted owl, the stumpage price trend to year 2010 is greater than 4.0%, and 0.0% to 2.0% thereafter. The increased use of recycled paper in the U.S. paper industry has the potential to reverse this trend. In this scenario, Douglas-fir stumpage price rises steeply (>4.0% per year) during the 1990s, and levels and falls between the years 2000 and 2040. Reduced export demand resulting from competition from Canada and southern hemisphere sources could further weaken price increases.

Although published projections of red alder stumpage price are not available, the following market forces are relevant. Ince (1989) projects that changes in pulping technology will increase the demand for hardwood chips nation-wide by the year 2040. Several hardwood furniture mills recently were established or expanded in Oregon.[2] The perceived scarcity of young red alder stands is causing concern over the long-term supply of red alder chips and sawlogs in the Pacific Northwest (Miner 1990). Red alder stumpage price may increase as a result of these forces; the uncertainty, however, is great.

[2] *Ralph J. Alig, USDA Forest Service, Pacific Northwest Experiment Station, Corvallis, OR, personal communication.*

Methods

The analysis of Douglas-fir and red alder management is presented in detail elsewhere (Haight, in press). The analysis extends work by Cleaves and Birch (1991) to include uncertainty in stumpage price trends, in addition to uncertainty in the degree of alder competition following reforestation. Management regimes include four kinds of treatment options: regeneration method, precommercial treatment, commercial thinning, and rotation age. Regimes are computed for Douglas-fir site indices 80, 100, and 120 (50-year basis).

Three regeneration options are defined to span a range of treatment intensities. The first two options are taken from Cleaves and Birch (1991). The high technology option (HITEC) involves piling and burning, planting 350 Douglas-fir trees/ac, and applying big game repellent and aerial herbicide. The cheap option (CHEAP) foregoes site preparation and chemical treatment, and plants 400 trees/ac. The third option assumes natural regeneration (NATURAL) with no treatment.

The stand condition 15 years after treatment depends on the success of the regeneration option (table 5). Each regeneration option may be successful, moderately successful, or a failure. For descriptive purposes, greater success means more Douglas-fir trees, higher stocking (percent of area covered with Douglas-fir), and fewer alder trees. The probability of success varies with the regeneration option; success is more likely with more intense treatment.

Mid-rotation management options include precommercial treatments and commercial thinning. Each regeneration option has three precommercial treatment options in year 15: no action, complete alder removal (100% success), or conversion to a new Douglas-fir plantation. Commercial thinning of Douglas-fir sawtimber may take place in year 35 (site indices 100 and 120) or year 45 (site index 80). The thinning options include leaving between 50 and 250 trees/ac in intervals of 50 trees/ac. No thinning is an option. Thinnings remove trees from below, which are merchandized as sawtimber (Scribner mbf/ac).

The final decision variable is the rotation age. The rotation options vary between 35 and 75 years in 5-year intervals. In the final harvest, Douglas-fir is sold as

Table 5.—Douglas-fir and red alder densities, stocking levels, and probabilities of occurrence 15 years after regenerating site index 100 land.

Regeneration success level	HITEC Density DF (trees/ac)	HITEC Density RA (trees/ac)	HITEC Stock (%)	HITEC Prob (%)	CHEAP Density DF (trees/ac)	CHEAP Density RA (trees/ac)	CHEAP Stock (%)	CHEAP Prob (%)	NATURAL Density DF (trees/ac)	NATURAL Density RA (trees/ac)	NATURAL Stock (%)	NATURAL Prob (%)
Success	300	5	90	90	200	50	90	75	200	150	80	50
Moderate	150	50	75	7	100	100	75	15	100	150	70	25
Failure	50	150	60	3	50	150	60	10	50	150	60	25

sawtimber (Scribner mbf/ac) and red alder is sold by the cubic foot (ft^3/ac). No assumption is made about whether alder is used for chips or sawlogs. The stumpage price should reflect its usage.

Estimates of Douglas-fir and alder yields are obtained with the Stand Projection System developed by Arney (1985). The simulator is used to project the stand conditions at age 15 forward to rotation age. The simulator predicts individual tree dimensions over time, and produces species-specific yield tables. Yields over time, for unthinned, stands are listed in table 6.

Table 6.—Douglas-fir and red alder volume yields[1] for three regeneration options and three levels of regeneration success, on site index 100 land.

Age (years)	HITEC DF (mbf/ac)	HITEC RA (mcf/ac)	CHEAP DF (mbf/ac)	CHEAP RA (mcf/ac)	NATURAL DF (mbf/ac)	NATURAL RA (mcf/ac)
			Success			
40	16.2	0.0	11.6	0.7	9.8	1.9
50	29.4	0.0	22.9	1.1	17.5	2.6
60	43.5	0.0	33.1	1.2	24.7	2.7
70	51.3	0.0	44.9	1.4	32.5	2.5
			Moderate			
40	8.6	0.8	5.9	1.6	5.3	2.1
50	17.0	1.2	11.6	2.5	9.5	3.2
60	25.6	1.4	17.5	3.2	14.9	4.0
70	33.2	1.4	23.3	3.6	19.5	4.1
			Failure			
40	2.7	2.2	2.7	2.2	2.7	2.2
50	4.9	3.4	4.9	3.4	4.9	3.4
60	7.4	4.2	7.4	4.2	7.4	4.2
70	9.9	4.9	9.9	4.9	9.9	4.9

[1] *Sawtimber yield is Scribner thousand board foot (mbf) per acre; pulpwood yield is thousand cubic feet (mcf) per acre.*

The following economic assumptions are included in the analysis. All prices and costs are in 1990 dollars. The regeneration cost is directly related to the intensity of regeneration treatment (Cleaves and Birch 1991): the HITEC option costs \$427/ac; the CHEAP option costs \$177/ac; and the NATURAL option costs \$0/ac. The cost of precommercial alder removal is \$1/tree. The additional cost of converting a 15-year-old stand to a new Douglas-fir plantation is \$100/ac.

Douglas-fir and red alder stumpage prices are expressed as probability histograms (fig. 4). The price distributions take effect in year 15, and are constant over the rotation.

The Douglas-fir price distribution (fig. 4A) assumes that price is likely to increase significantly from its 1990 level. The price distribution ranges from \$160 to \$320/mbf; the most likely price class is \$320/mbf. For comparison, the average stumpage price in 1990, for the Douglas-fir region of the Pacific Northwest, is about \$160.00/mbf (Haynes 1990). The most likely price forecast (\$320/mbf) is a 5% average annual increase over 15 years.

The red alder price distributions represent two different outlooks. In the pessimistic distribution (fig. 4B), price classes range between \$0.00 and \$0.40/ft^3, with a most likely class of \$0.20/ft^3. In the optimistic distribution (fig. 4C), price classes range between \$0.20 and \$1.60/ft^3, with a most likely class of \$0.40/ft^3. For comparison, the 1989 average delivered red alder pulpwood price in Oregon is \$0.64/ft^3 (Cleaves and Birch 1990). Assuming that logging and transportation costs are 60% of the delivered price, the state-wide average stumpage price is \$0.25/ft^3.

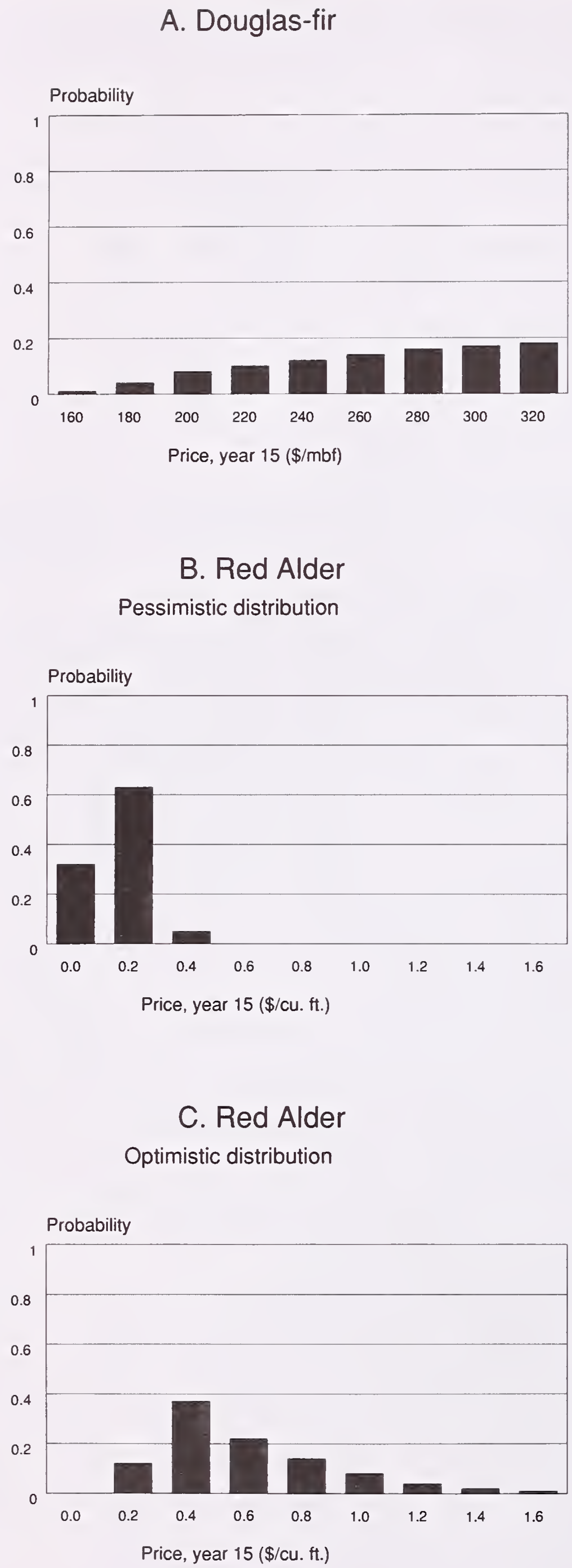

Figure 4.—Probability histograms for Douglas-fir and red alder stumpage prices in year 15.

Each price distribution is computed using Monte Carlo simulation. The initial Douglas-fir price is $160/mbf. Representing a range from low to high values, the initial pulpwood price is either $0.10 (fig. 4B) or $0.40/ft^3 (fig. 4C). The 15-year trends for Douglas-fir and red alder prices are independent random variables with triangular probability distributions. For Douglas-fir prices, the minimum and maximum trends are 0% and 5%, respectively, with a most likely trend of 5%. For red alder prices, the minimum and maximum trends are -5% and 10%, with a most likely trend of 0%.

At rotation age, the returns include the revenue from clearcutting and the value of bare land. The bare land value is the present value of an infinite series of rotations, assuming no risks in future management. If the stand is converted to a Douglas-fir plantation in year 15, the bare land value is added to the cost of conversion. The real discount rate is 4%. Taxes and management costs are not included.

The purpose of the decision analysis is to determine the best treatments as a function of the stumpage prices and degree of regeneration success and to determine the EPVs of the regeneration options. The analysis is described with the aid of the decision tree in figure 5. The management decisions are represented by square boxes, and the analysis starts with the rotation-age decision and moves backward in time to the regeneration decision.

The circles represent two stochastic events: year 15 prices and regeneration success. Price-class probabilities for Douglas-fir and red alder are given in figure 4. The regeneration success probabilities (table 5) are taken from Cleaves and Birch (1991). The EPV of each regeneration option is the difference between the weighted average of the present values optimal actions in year 15 and the regeneration cost.

Results

Regeneration and Precommercial Thinning

The EPV rankings of the regeneration options depend on site index (table 7). As site index increases, Douglas-fir productivity increases,and the EPV of the HITEC option increases relative to the other options. For site index 120, the EPVs of the HITEC option are up to 14% greater than the EPVs of the CHEAP and NATURAL options. In contrast, on site index 80 land, the NATURAL option has the highest EPVs, which are up

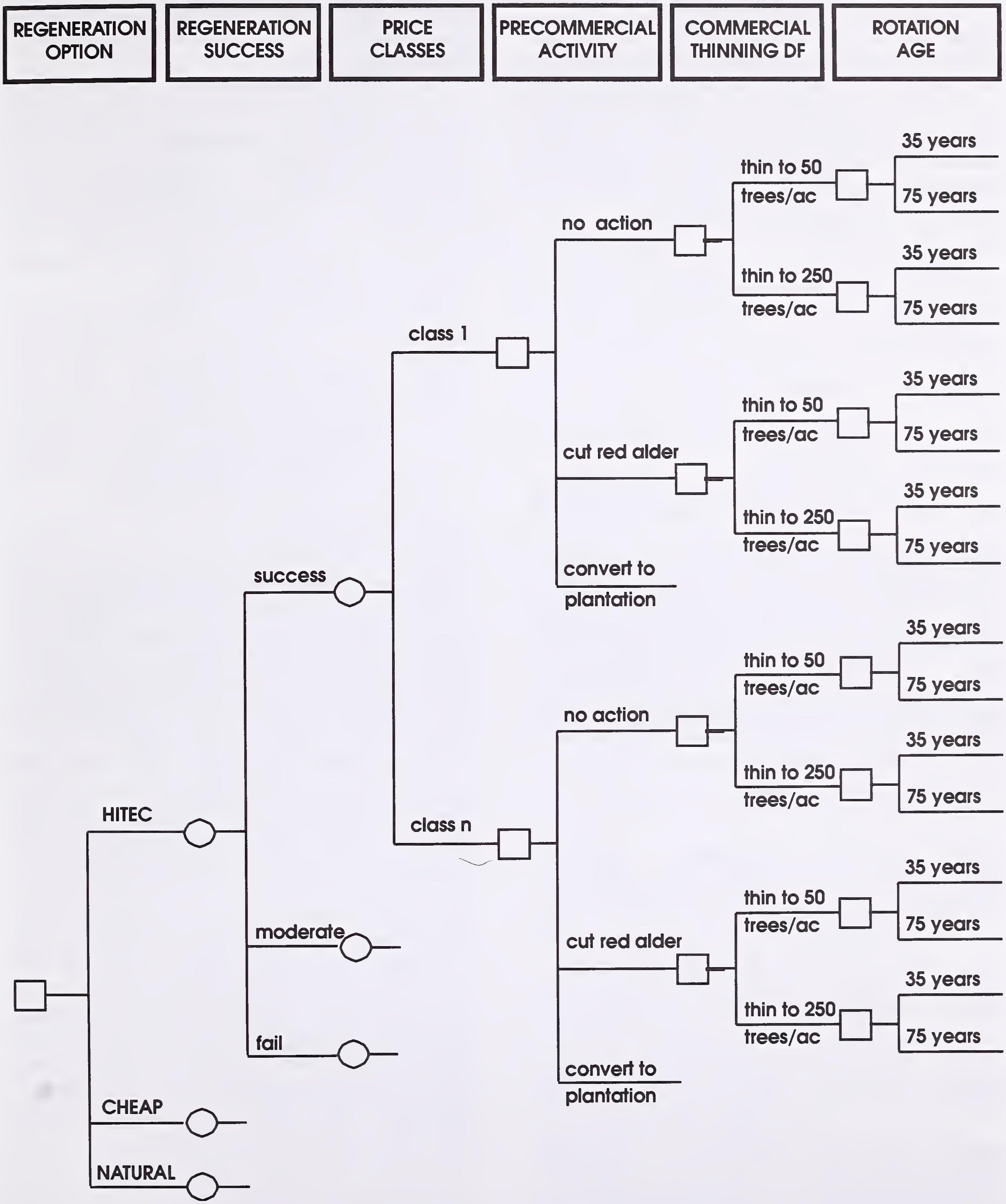

Figure 5.—A portion of the decision tree for determining optimal management actions for Douglas-fir and red alder regeneration options.

to 64% greater than the EPVs of the HITEC option. The rankings for site index 100 stands are mixed and depend on the stumpage price distribution for red alder. With the pessimistic distribution, the HITEC option has the highest EPV because it is likely to have the smallest amount of alder competition, and the likelihood of relatively low red alder prices is high. With the optimistic distribution, the NATURAL option is superior, because the fixed cost is zero, and the likelihood of high red alder prices is high.

In addition to EPV, the minimum present value for each regeneration option may influence the decision. The simulation results show that the range of present values for the HITEC option includes negative returns (table 7). These occur when price trends are zero or less, and the present value of harvest does not offset the high regeneration cost. The minimum present values for the CHEAP and NATURAL options are positive, because regeneration costs are lower.

The management actions in year 15 and the subsequent rotation age depend on both regeneration success and stumpage prices in year 15. For example, table 8 shows the best actions for a site index 100 stand, when the Douglas-fir price in year 15 is \$330/mbf. When the red alder price in year 15 is low (\$0.10/ft^3), removing the red alder or regenerating the stand is superior. For a higher red alder price (\$0.50/ft^3), no action is usually preferred. In this case, the present value of a mixed-species stand is superior to the present value of a pure Douglas-fir plantation.

The NATURAL option performs well on low and moderate site indices; its EPV is close or superior to the EPVs of the other options (table 7). The NATURAL option is superior, in part, because its regeneration cost is low. Further, the decision to cut red alder is postponed for 15 years, and is contingent on the red alder price. If the price is low and precommercial thinning is undertaken, the cost is discounted in comparison to red alder removal soon after regeneration.

A key assumption with the NATURAL option is that the Douglas-fir volume (when converted to ft^3/ac) is likely to be greater than the red alder volume. The performance of the NATURAL option is sensitive to successful Douglas-fir regeneration; as the likelihood of fewer Douglas-fir trees and lower stocking increases, the EPV of the NATURAL regeneration option drops in comparison to the EPV of the HITEC option.

Table 7.—Mean[1] and minimum present values for Douglas-fir and red alder regeneration options without commercial thinning.

Red alder price distribution	HITEC mean	HITEC min	CHEAP mean	CHEAP min	NATURAL mean	NATURAL min
	(\$/ac)					
			Site index 80			
pessimistic	150±9	-310	227±7	-67	316±7	110
optimistic	158±8	-275	297±7	-4	440±8	169
			Site index 100			
pessimistic	734±16	-138	695±16	60	695±16	237
optimistic	747±15	-88	801±14	177	854±15	340
			Site index 120			
pessimistic	1,327±23	61	1,220±24	219	1,137±23	396
optimistic	1,339±22	169	1,319±21	392	1,299±22	535

[1] *Mean present values include an approximate 95% confidence interval.*

Commercial Thinning

Including commercial thinning options for Douglas-fir produces statistically significant increases in the EPVs of the HITEC regeneration option, on site indices 100 and 120. The EPVs of these regimes are between 6% and 10% greater than the EPVs of corresponding regimes without thinning; however, the EPV rankings of the regeneration options do not change.

Commercial thinning increases the EPV of the HITEC regeneration option primarily because, in stands with successful Douglas-fir regeneration, commercial thinning provides early returns while maintaining a high yield at rotation. Regardless of the Douglas-fir and alder prices in mid-rotation, stands are thinned to 200 trees/ac and are clearcut in year 50. In stands with moderately successful regeneration, thinning is efficient when alder price is high relative to Douglas-fir (e.g., for site index 100, when the alder price is greater than \$0.5/ft^3, and the Douglas-fir price is \$160/mbf). In this case, thinning Douglas-fir provides an early return while increasing alder yield at rotation. For the same reason, commercial thinning is efficient in the CHEAP and NATURAL regeneration options only when alder price is high relative to Douglas-fir.

Table 8.—Management actions and rotation ages for Douglas-fir and red alder regeneration options as a function of regeneration success and red alder price in year 15. The Douglas-fir price is $330/mbf and the site index is 100.

	Regeneration options					
Regeneration	HITEC		CHEAP		NATURAL	
success level	Year 15 action	Rotation age (yr)	Year 15 action	Rotation age (yr)	Year 15 action	Rotation age (yr)
			Red alder price = $0.1/ft^3			
Success	Cut RA	50	Cut RA	55	Cut RA	55
Moderate	Cut RA	55	Cut RA	55	Cut RA	55
Failure	Convert	15	Convert	15	Convert	15
			Red alder price = $0.5/ft^3			
Success	Cut RA	50	No action	50	Cut RA	55
Moderate	No action	50	No action	50	No action	45
Failure	No action	45	No action	45	No action	45

SUMMARY OF RESULTS

Including stochastic regeneration outcomes and stumpage prices in the economic analysis of reforestation options adds insight that is missed with deterministic analysis. The stochastic analysis allows the development of a range of likely present value outcomes as well as the mean outcome. Further, stochastic analysis allows the development of rules for adjusting management actions in mid-rotation, as a function of new information about stand and economic conditions. The results from the case studies provide examples of these insights.

The surprising result is the economic performance of low-cost regeneration options. In two measures of performance—expected present value and minimum present value—low-cost reforestation options that result in mixtures of softwoods and hardwoods are superior to intensive reforestation efforts, in some situations, in both loblolly pine and Douglas-fir timber types. For the loblolly pine type, the EPV of the low-cost option is superior across a range of site indices, when pine dominates hardwoods after reforestation, and when markets exist for both pine and hardwood thinnings. For the Douglas-fir type, the economic performance of the low-cost option is superior on land with lower site indices, assuming that Douglas-fir is likely to dominate red alder and that precommercial thinning of red alder is an option. In these situations, the low-cost options gain economic advantage, because mixed-species stands include the option to change species composition and density in mid-rotation, contingent on the relative prices of the species.

This finding contrasts with previous studies (Brodie et al. 1987; Guldin and Guldin 1990) that show the economic superiority of intensive site preparation and planting. Intensive management is superior in these cases because of pessimistic assumptions about hardwood stumpage price and hardwood competition. These pessimistic assumptions may be incorrect, given the development of low-cost regeneration methods that control species composition (Phillips and Abercrobie 1987) and the changes in pulp and paper technology that may increase the demand for hardwood pulpwood (Ince 1990).

There are cautions about the main result. The superior performance of low-cost regeneration options depends on the likelihood of softwood dominance after reforestation. In the cases presented here, loblolly pine is assumed to compose about 70% of the stand basal area, and Douglas-fir trees are likely to outnumber red alder trees 15 years after low-cost reforestion efforts. In both cases, increasing the likelihood of hardwood dominance reduces the EPVs of low-cost regeneration options. This sensitivity points out the importance of accurate estimates of probabilities of species composition and stocking after regeneration.

The superior performance of the low-cost options also requires that thinning is an option in mid-rotation. In pine-hardwood stands, hardwoods should be re-

moved in a commercial thinning regardless of the hardwood stumpage price. In Douglas-fir and red alder stands, red alder should be cut in a precommercial thinning, if its price is low. If thinning is not an option, the EPVs of low-cost regeneration options drop because, for many price scenarios, growing a mixed-species stand to rotation has a lower present value than that of a pure conifer stand.

A second surprising result is the gain in present value that can be obtained with judicious timing of the final harvest. For mature loblolly pine stands, a simple rule of cutting when the stumpage price is above the historical average may increase EPVs by 20% or more, in comparison to the EPVs of fixed rotation ages. Such gains assume that the stationary process underlying past price changes continues in the future. To apply this rule, the landowner must monitor short-term (e.g., quarterly) stumpage prices, and must be ready to complete a timber sale contract. These requirements show the importance of price reporting services and timber marketing specialists.

RPA IMPLICATIONS

The results suggest that, with improvement in low-cost methods for establishing mixed conifer and hardwood stands, and with improvement in the markets for hardwoods, low-cost silviculture is a viable economic option that compares favorably with intensive plantation management. There are two implications for the RPA Assessment and Program.

- First, if one of the goals of the RPA Assessment is to identify economically attractive management options that will increase timber production on non-industrial forest lands, the RPA Assessment should recognize the economic qualities of low-cost regeneration options that may attract non-industrial forest landowners: low initial investment, competitive expected present value, and low risk of negative present value. Further, because mixed-species stands often satisfy non-timber goals (e.g., wildlife habitat, visual quality), the RPA Assessment should recognize that the results of low-cost regeneration options may satisfy both economic and environmental objectives that are difficult to attain with intensive forest practices.
- Second, if forest landowners widely adopt low-cost silvicultural options, the nature of silviculture and forest conditions in the Pacific Northwest and South would change from previous projections that assume widespread intensive plantation management. The market impacts of these changes have not been determined.

FUTURE RESEARCH

While this analysis has focused on the impacts of risky stumpage prices on economic returns, the case studies point out that estimates of biological risk are equally important. Elements of biological risk that should be included in the decision analysis are variability in species composition and growth after reforestation, and variability in merchantable yield. Silvicultural studies of the influence of herbacious and woody competition on conifer growth after reforestation, (Cain 1991; Miller et al. 1991) provide a basis for better probability estimates. Long-term observations of the influence of planting density on merchantable conifer yields (Buford 1991) provide a basis for estimating yield variance.

This analysis focused on management options for a single stand of trees; yet, many landowners manage several stands and have varying degrees of risk aversion. An approach to this problem is to formulate a forest-level model that incorporates several reforestation options. The model would analyze the mean-variance tradeoffs between different combinations of options, and would choose the strategy that best accommodates the landowner's attitude toward risk (Reed 1991).

This analysis also focused on the economics of timber production and has ignored the projection and evaluation of non-timber outputs, which, in many cases, are equally important. Methods for evaluating tradeoffs between forest outputs have been developed for single stands (Haight et al. 1992); but, many forest outputs (e.g., viable populations of wild animals) depend on the spatial arrangement and age structure of many stands. National forest planning models have significant limitations: (1) their linear structure is incompatible with forest outputs that are nonlinear and related to the spatial arrangement of vegetation, and (2) the models ignore the uncertainties about the relationship between vegetation structure and forest outputs. Stochastic, spatial models are needed to analyze tradeoffs between forest management activities and environmental protection.

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